

Combretum-Terminalia vegetation accumulates more carbon stocks in the soil than the biomass along the elevation ranges of dryland ecosystem in Southern Ethiopia

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ABSTRACT

Dry land ecosystems including Combretum-Terminalia vegetation cover a wider area in the tropics. These resources are believed to greatly contribute for climate change mitigation in dry land ecosystems. Therefore, the objective of this study was to investigate biomass and soil carbon stocks of Combretum-Terminalia vegetation along the elevation ranges. A total of 60 nested sample plots of 20 m × 20 m were laid systematically along lower, middle and higher elevation ranges, representing 20 plots for each elevation. Within each nested sample plot inventory of woody species, litter and soil samples (0–15, 15–30 cm layers) were collected. The total carbon stocks (biomass plus soil) significantly ($p < 0.05$) differed among the three studied elevation ranges. The biomass carbon stocks were not significantly different between middle and higher elevations but both of them significantly ($p < 0.05$) differed from lower elevation, and also showed a decreasing trend from lower to higher elevations. However, inconsistency trends were observed for soil organic carbon and litter along the elevation ranges. It was concluded that woodland ecosystem has a potential to accumulate higher carbon stocks in the soil than the biomass and significantly vary along elevations.

1. Introduction

The increasing concentration of carbon dioxide (CO₂) and other greenhouse gases (GHG's) in the atmosphere is now widely recognized as the main cause of global warming. Carbon dioxide is accumulating in the atmosphere at a rate of 2.06 ppm (ppm = 10⁶ molecules of air) per annum during the last ten year, the largest proportion of which resulting from burning of fossil fuels, cement production, deforestation and other land use changes (WMO, 2014). One of the strategies to reduce carbon dioxide from atmosphere through carbon sequestration in forest resources (Sheikh et al., 2009) and is well recognized under Kyoto Protocol (UNFCCC, 1997). These sinks can be in the living biomass (above-and-belowground), in soil including fine roots and in the deeper sub-surface environments (Nair et al., 2009) and locking carbon (C) in the products (IPCC, 2014).

Globally, dry land ecosystems store approximately 36% (743 Gt) of the total carbon stocks in the biomass with carbon sequestration rate of 0.4–0.6 billion tons of carbon per year. While forest ecosystems of Africa are estimated to store 356 Gt of carbon in the biomass. Of which dry land forest accounts for 59% carbon stocks (Campbell et al., 2008). Thus, managing the dry forest and woodland ecosystems is a carbon

sequestering strategy to contribute to global carbon cycle (Smith et al., 1993; Dixon et al., 1994; Lal, 2005).

In Ethiopia, dry lands cover approximately 71.5% of the landmass (Lemenih and Teketay, 2004). Of which the woodland ecosystem covers 25.8%, which is equivalent to sequestering 1263.1 million tons of carbon (WBISPP, 2005; Yitebitu et al., 2010). However, loss of dry forests of Ethiopia is occurring through the destruction of habitat owing to extensive deforestation and conversion of forests to agricultural lands (Mekuria et al., 1999). The recognition of these resources in mitigating climate change on the other hand and also the effect of elevation range on biomass and soil carbon stocks have hardly studied (Houghton, 2007; Aide et al., 2012; Gillespie et al., 2012). While understanding the forest carbon storage and allocation along elevation ranges will help us better predict the response of dryland forests to regional and global carbon balance to future climate (Girma et al., 2014).

Besides, dry forest dependent communities would be beneficiaries from future payment for ecosystem services particularly carbon financing scheme through maintaining woodland resources (Alemu, 2012). Therefore, this study aimed at investigating the potentials of Combretum-Terminalia woodland in southern Ethiopia for biomass and soil carbon stocks and its variations along elevation ranges.

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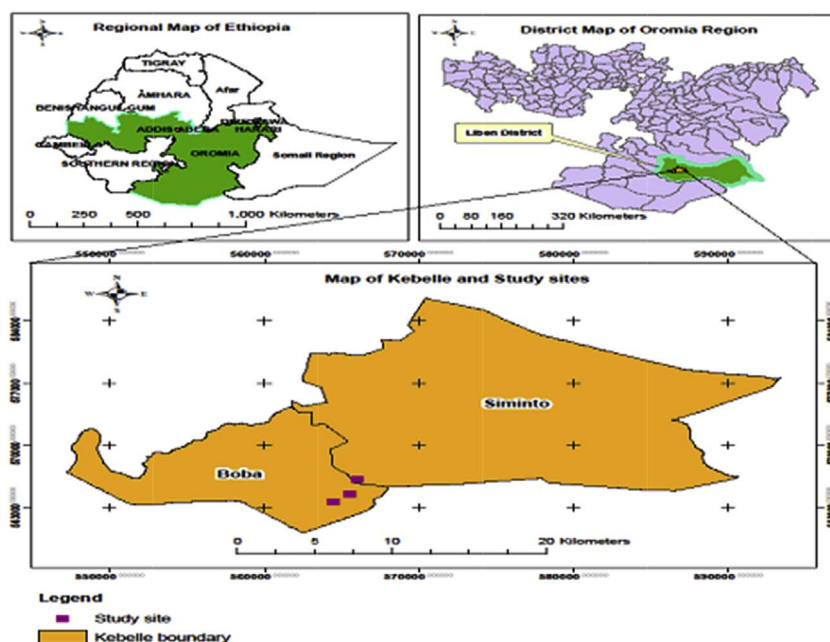


Fig. 1. Map of the study site.

2. Material and methods

2.1. Study area

The study was conducted in Liben Woreda of Guji zone, Oromia Regional State of Ethiopia. It is located at about 630 km south of Addis Ababa (Fig. 1). Geographically, it is situated between 5° 5' 10" N to 5° 7' 50" N latitude and 39° 32' 30" E to 39° 36' 30" E longitude. Except for the central mountain range and scattered volcanic cones and craters, the landscape is dominantly gentle elevation between 1000 and 1600 m.a.s.l (Coppock, 1994).

According to Ethiopian National Meteorology agency weather data from 2000 to 2014, the mean minimum and maximum temperature of the study area was 16 °C and 28 °C, respectively. The mean annual rainfall was 609 mm. Vegetation of study areas falls under *Combretum-Terminalia* dominated woodland (Haugen, 1992). Besides, species such as *Combretum molle* (D. Don), *Terminalia brownii* (Fresen.), *Acacia bussei* (Harms ex Sjoestedt), *Pistacia lentiscus* (Mart.), *Commiphora africana* (A. Rich.)Engl., *Lannea rivae* (Chiov.) Sacleux, and *Olea europaea* subsp. *Cuspidate* (Wall. G. Don) are commonest trees species in the studied area. The upland soils are shallower, well-drained, red sandy soils and the vertisols in the lower elevation (Coppock, 1994).

2.2. Sampling techniques

Three elevation ranges, namely higher (1520–1620 m), middle (1420–1520 m) and lower (1320–1420 m), were purposively set along elevation ranges in the study area. A systematic random sampling technique was employed. A total of sixty plots (2 sites x 3 elevation ranges x 10 sample plots) sized 20 m x 20 m were systematically established. Transects were laid using GPS and compass. The sample plots were used to collect biomass, litter and soil C stocks data. In order to eliminate any influence of the edge effects on the forest biomass, all sample plots were laid at least 150 m away from nearest roads.

2.3. Woody species inventory and identification

All trees in the sample plot with diameter at breast height ≥ 5 cm, and total tree height ≥ 1.5 m were measured and recorded. Besides, trees on the border of the plot were measured if $\geq 50\%$ of their basal

area fall within the plot otherwise were excluded. Trees with their trunks inside the sampling plot and branches outside were also considered (MacDicken, 1997). In the occasion of multi-stemmed woody species, each stem was measured and the equivalent diameter of the plant calculated as the square root of the sum of diameters of all stems per plant (Snowdon et al., 2002).

$$d_e = \sqrt{\sum_{i=1}^n d_i^2}$$

where d_e is diameter equivalent (at breast or stump height), d_i is diameter of the i th stem at breast or stump height (cm).

Plant specimens were collected, dried, and identified at the National Herbarium of the Addis Ababa University and using published volumes of Flora of Ethiopia and Eritrea (Hedberg and Edwards, 1995; Edwards et al., 1997, 2000).

2.4. Litter and soil sampling

Litter samples were collected in a 1 x 1 m² square sub-plot within the sixty larger plots. A total of five sub-plots (four at corners and one in the center) were used for litter collection. The litter samples in this study comprised dead leaves, branches, twigs, flowers, and dead wood. The fresh litter within each 1 m² sub plot was collected and weighed on the site. A composite sample of 100 g was taken for laboratory analysis to oven drying at temperature of 65 °C for 24 h until it attained constant weight. This helped to determine the dry to fresh weight ratio. The total dry weight was determined in the laboratory using dry ashing method as per Allen et al. (1986). Finally, carbon in leaf litter for each site was determined.

Soil samples for determination of soil organic carbon (SOC) were collected from the five sub-plots that were used for litter collection. A total of 120 soil samples (2-sites replication x 3-elevations x 10-plots x 2- depths) were collected from soil depths of 0–15 and 15–30 cm. The soil samples for carbon analysis were collected using augur of 8 cm diameter while soil samples for bulk density were collected with soil core samplers of (5 cm diameter x 5 cm tall, 98.2 cm³). All samples were placed in paper bags with appropriate label. The soil samples for carbon analysis were air dried and sieved with 2 mm sieve for SOC determination to mineral soil fraction of < 2 mm. The C content of the

Table 1

Biomass carbon stocks (Mean $\pm$ SD, Mg ha⁻¹) along elevation ranges of dryland ecosystem in Southern Ethiopia (n = 20 plots each).

Carbon stock	Elevation			F	P
	Lower	Middle	Higher		
AGBC	20.0 $\pm$ 6.7 ^a	12.0 $\pm$ 5.5 ^b	11.2 $\pm$ 5 ^b	14.2	< 0.0001
BGBC	5.2 $\pm$ 1.8 ^a	3.1 $\pm$ 1.4 ^b	2.9 $\pm$ 1.3 ^b	13.8	< 0.0001
Litter carbon	0.19 $\pm$ 0.1 ^b	0.4 $\pm$ 0.1 ^a	0.21 $\pm$ 0.1 ^b	36.7	< 0.0001
Total	25.4 $\pm$ 8.4 ^a	15.5 $\pm$ 6.9 ^b	14.3 $\pm$ 6.3 ^b	14.1	< 0.0001

AGBC = above ground biomass carbon; BGBC = below ground biomass carbon.

Similar letters show no significant differences, and different letters indicate significant differences between groups at $p < 5\%$.

soil samples was determined using the Walkley-Black (Walkley and Black, 1934). A correction factor of 1.33 was used to the incomplete oxidation of organic carbon in the Walkley-Black method (Rosell et al., 2000). For bulk density analysis the soil samples were oven-dried at 105 °C for 48 h and then, weighed.

2.5. Estimation of biomass carbon stocks

Biomass carbon stocks were estimated on the basis of dry matter biomass and carbon content. The estimation of aboveground biomass (stem, branch, foliage, bark) was calculated using allometric equation developed by (Chave et al., 2014):

$$AGB = 0.0673 \times (\rho D^2 H)^{0.976}$$

where: AGB = Aboveground biomass (kg/tree), ρ = Wood density, g/cm³, DBH = Diameter at breast (cm), H = Height (m).

The Chave et al.'s equation was selected because it covers a wide range of climatic conditions and vegetation types including tropical forests, subtropical forests, and woodland savannas (Chave et al., 2005, 2014). The Chave et al.'s equations represented a major step forward in tropical forest carbon accounting. They are also currently being proposed for inclusion in the IPCC emission factor database and REDD⁺ protocols (IPCC, 2007).

Wood density values (oven-dry mass per unit of green volume) for each species were adapted from global wood density database (Zanne et al., 2009). Default value of 50% carbon content was used to convert the biomass to carbon stocks.

The belowground biomass (stump plus coarse roots, > 2 cm diameter) was calculated based on the proportion of 26% of the above ground biomass (Cairns et al., 1997). Carbon stocks in litter were calculated by multiplying litter dry weight per area with the relative carbon concentration of the samples using (Pearson et al., 2005).

2.6. Estimation of soil organic carbon

The soil organic carbon (SOC) stock was calculated as follows (Pearson et al., 2005):

$$SOC = BD \times D \times \% C \times 100$$

where: SOC = Soil Organic Carbon stock per unit area (Mg/ha), BD = soil bulk density (g cm⁻³ < 2 mm), D soil layer (cm) the sample was taken, C = Carbon concentration (%). Then, coarse fraction content (> 2 mm) was corrected by multiplying by (100% - volumetric content of coarse fraction, %)/100%). The volumetric content of the coarse fraction was calculated from the gravimetric contents of > 2 mm material in the soil samples and an assumed density of solids value of 2.65 g cm⁻³. The SOC stock of 0–30 cm was calculated based on summing up the carbon stock in 0–15 cm and 15–30 cm soil layers.

The total carbon stock for the studied system was estimated by summing up the carbon stocks in the biomass (aboveground, belowground and litter) and SOC stocks.

2.7. Statistical analyses

The C stocks (Mg ha⁻¹) of the trees, litter and soil were calculated for each of the 60 plots. The size and variation in the C stocks for each elevation were described by the mean and standard deviation. To test for differences in C stocks between the three elevation range one way and two way ANOVA were performed ($\alpha = 0.05$). Levene's test was used to check for the homogeneity of variances (homogenous in all cases). To test for differences between biomass C and SOC stocks, paired t-tests were computed. SAS 9.0 was used for the statistical analysis.

3. Results

3.1. Biomass carbon stocks along elevation ranges

The aboveground biomass carbon stocks for woody species did not significantly differ between middle and higher elevations but both of them significantly ($p < 0.05$) varied from lower elevation (Table 1). The aboveground biomass carbon stock for lower elevation was by 40 and 45% higher than middle and higher elevations, respectively. Among the dominant species, *Acacia bussei* (Harms ex Sjöstedt) recorded 71.3% of the aboveground biomass carbon stocks in lower elevation and *Combretum molle* (D. Don) accounted for 39.6% and 36.8% in the middle and the higher elevations, respectively. *Acacia bussei* (Harms ex Sjöstedt) recorded 34.8% of the total aboveground biomass carbon across the three studied elevation ranges.

Similar to the aboveground biomass carbon stocks, belowground biomass carbon stock showed decreasing trend with increasing elevation. The belowground biomass carbon stock in the lower elevation was significantly ($p < 0.05$) different from the remainder two elevation ranges. The mean belowground biomass carbon stocks ranged from 2.9 to 5.2 Mg ha⁻¹ in the three studied elevation ranges (Table 1).

The litter biomass carbon stock in the middle elevation significantly differed from both lower and higher elevations ($p < 0.05$). The highest litter biomass recorded in middle elevation, followed by higher and lower elevations (Table 1).

3.2. SOC stocks along elevation ranges

SOC stocks across elevation ranges and the soil depths are shown in Table 2. SOC stocks for soil surface layer (0–15 cm) followed similar trend that of litter biomass carbon stocks. However, SOC for the sub-soil depth (15–30 cm) and the total (0–30 cm) showed inconsistency trend but they were significantly differed along elevation ranges ($p < 0.05$). The total SOC (0–30 cm) stocks ranged from 51.2 to 120 Mg ha⁻¹. The SOC (0–30 cm) in the middle elevation was higher by 57.3% and 24% than lower and higher elevations, respectively. The contribution of upper soil (0–15 cm) to total SOC stocks were highest for lower elevation (58%), followed by higher (55%) and middle (53%) elevations. However, the contribution of sub-soil depth (15–30 cm) to total SOC stocks were highest for middle elevation (47.4%) and followed by higher (45%) and lower (42%).

3.3. Total ecosystem carbon stocks

The total ecosystem carbon stocks (biomass, litter, soil 0–30 cm) differed along elevation ranges (Fig. 2). The total woodland ecosystem carbon stocks significantly differed ($p < 0.05$) along the three studied elevation ranges. The highest ecosystem carbon stock was recorded for middle elevation (135.5 $\pm$ 22.8 Mg ha⁻¹) and the least was for lower elevation (76.51 $\pm$ 25.8 Mg ha⁻¹). The contribution of biomass carbon to the total ecosystem carbon stock was the highest for the lower elevation (33%), followed by higher elevation (13%) and middle (11%), implying consistence trend of total biomass carbon contribution along elevation ranges. Similarly, the contribution of litter carbon to total ecosystem carbon stocks was relatively higher in the middle elevation

Table 2

Soil organic carbon stocks (mean $\pm$ SD, Mg ha⁻¹) along elevation ranges dryland ecosystem in Southern Ethiopia (n = 20 plots each).

Soil depth, cm	Elevation			F	P
	Lower	Middle	Higher		
0–15	29.7 $\pm$ 13.6 ^b	63.1 $\pm$ 12.2 ^a	50 $\pm$ 26.7 ^a	16.3	< 0.0001
15–30	21.5 $\pm$ 15.6 ^c	56.9 $\pm$ 9.6 ^a	41.1 $\pm$ 19.2 ^b	26.8	< 0.0001
0–30	51.2 $\pm$ 21.3 ^c	120 $\pm$ 17.2 ^a	91.1 $\pm$ 43.2 ^b	27.4	< 0.0001

Similar letters show no significant differences, and different letters indicate significance differences between groups at $p < 5\%$.

The effect of elevation, soil depth and elevation $\times$ soil depth on SOC stocks are shown in Table 3. The soil organic carbon significantly affected by elevation and soil depth ($p < 0.05$). However, the interaction of elevation and soil depth did not significantly affect the soil organic carbon ($p > 0.05$).

Table 3

Mixed model effects of elevation and depth on SOC.

Response variable	DF	F	p-value
Elevation	2	41.01	< 0.0001
Depth	1	6.23	0.014
Elevation $\times$ Depth	2	0.06	0.94

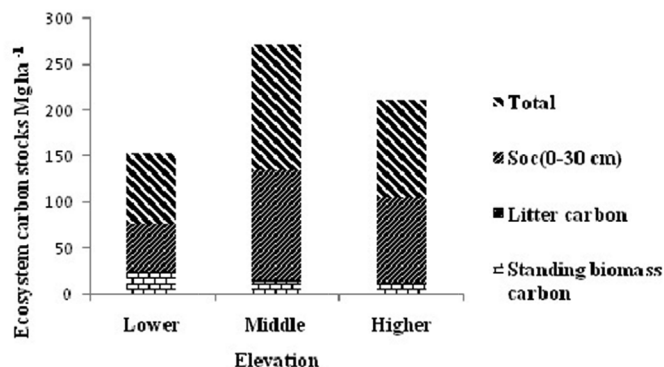


Fig. 2. Mean ecosystem carbon stock among the three elevation gradient.

range than the remainder two studied elevation ranges, showing that the litter carbon stocks followed the trend of SOC along elevations. SOC over the total carbon stocks was the highest for the middle elevation (89%), followed by higher (87%), and lower (67%) elevations.

4. Discussion

4.1. Biomass carbon stocks

The mean above ground biomass carbon stock along elevation ranges recorded in our study was within the range of tropical dry forest (14–123 Mg ha⁻¹) [Murphy and Lugo \(1986\)](#), Sub-Saharan Africa tropical dry forest (17–72 Mg ha⁻¹) [Gibbs et al. \(2007\)](#) and tropical dry deciduous forests of recorded in other part of the tropics (14.7–43.2 Mg ha⁻¹) ([Chaiyo et al., 2011](#)). Besides, similar findings were reported for Miombo woodlands of Tanzania (19.2 Mg ha⁻¹) [Munishi \(2010\)](#) and African tropical dry forest (10–34 Mg ha⁻¹) ([Henry, 2010](#)). However, the present finding was lower than those found for semi-arid savannas woodland in Ethiopian (25.9 Mg ha⁻¹) [Sarah \(2012\)](#) and in tropical and subtropical dry forests elsewhere in the tropics (36–85.5 Mg ha⁻¹) ([Weaver and Murphy, 1990](#)). The variation with other studies could be due to variation in stand structure and composition, topography, elevation, disturbance factors such as forest fire and human interventions including livestock free grazing, wood harvest, and climatic factors ([Chave et al., 2004](#)).

Besides, the belowground biomass carbon stocks in the present study were lower than the global average values of tropical dry forest (10–45 Mg ha⁻¹) ([Murphy and Lugo, 1986](#)). But, it is similar with that what was reported for woodland ecosystem of north western lowlands of Ethiopia ([Alemu, 2012](#)).

The mean litter biomass carbon stocks along the elevation ranges in the present study were lower than what was reported by [Brown and Lugo \(1982\)](#) in dry tropical forests (2.52–3.69 Mg ha⁻¹) and other studies reported elsewhere in the tropics ([Feyissa et al., 2013](#); [Girma et al., 2014](#); [Wolde et al., 2014](#); [Yelemfrhat et al., 2014](#)). However, the present findings were comparable with the findings of [Alemu \(2012\)](#) in woodland ecosystem of north western lowlands of Ethiopia. The variation with other studies could be due to the difference in rate of litter decomposition that is governed by climatic factor (temperature and moisture). It is known that increase in temperature would increase the decomposition rate and vice versa. Moreover, forest vegetation characteristics (species, age and density) and elevation could be attributed to the variation of litter accumulation ([Fisher and Binkley, 2000](#)).

4.2. Soil carbon stocks

The soil organic carbon stock recorded in our study was within the range of African savannas and woodlands (30–140 Mg C ha⁻¹) [Ciais et al. \(2011\)](#) and Sahelian savanna woodlands (20–120 Mg ha⁻¹) for similar soil depth ([Saiz et al., 2012](#)). The present findings were also comparable with those found in dry land ecosystem in Southern Ethiopia ([Wolde et al., 2014](#)), semi-arid pastoral ecosystems of northern Kenya [Hallo et al. \(2014\)](#), South African Miombo woodlands [Williams et al. \(2008\)](#) and Tanzanian Miombo woodlands ecosystems [Shelukindo et al. \(2014\)](#) and they were higher than soil organic carbon of woodland in Southern lowland of Ethiopia ([Belay and Kebede, 2010](#)). The difference with other studies might be due to the soil physical structure, species composition and the rate of litter decompositions ([Rojas et al., 2012](#)). For instance, the influence of climate on soil C stocks could be related to the role of soil micro-organisms affecting SOC stability, as the soil microflora is highly sensitive to moisture [Coûteaux et al. \(1991\)](#), and decompose organic matter would be more rapid with increasing temperature ([Knorr et al., 2005](#)).

The SOC stock in our study was higher in surface soil layer. This may be due to the accumulation of soil organic matter in the top soil. The variations of SOC in our study along elevation ranges were comparable with studies conducted in other similar studies ([Feyissa et al., 2013](#); [Girma et al., 2014](#)).

4.3. Ecosystem carbon stocks

The studied woodland ecosystem store high carbon stocks (76.5–135.5 Mg ha⁻¹) along the elevation ranges. The present finding also comparable with total carbon stocks found in semi-arid pastoral ecosystems of northern Kenya ([Hallo et al., 2014](#)). Additionally, the largest store of carbon in Ethiopia is found in woodlands ecosystem, accounting about 46% of woody biomass carbon stocks ([Yitebitu et al., 2010](#)). This contributes to climate change mitigation besides supporting the pastoral community. The higher carbon stock in our ecosystem was contained in the soil than biomass. This could be due to the accumulation of fine roots, and high input of litter. Similar findings were found in other studies ([Girmay et al., 2008](#); [Ryan et al., 2010](#)). The more carbon stocks in the soil would be a good opportunity to preserve carbon in long-term. Soil carbon sequestration could also be more preferred than biomass carbon that ultimately decomposes. Besides, soil carbon sequestration enhances the food productivity, nutrition security, sustaining water flow and quality, improving biodiversity, and strengthening elemental recycling ([Lal et al., 2015](#)).

Besides carbon accumulation, the woodland ecosystems in Africa play important role in adapting to climate change impacts ([Munishi, 2010](#)). However, extensive deforestation currently being carried out in

Combretum–Terminalia dry lowland of Ethiopia destroyed 650,000 ha between 2000 and 2013 (Franks, 2017). This calls for urgent efforts to preserve these dry land ecosystems to cope up impact of climate change and enhance other ecosystem services. This would also create an opportunity to benefit from future payment of ecosystem services and carbon financing and improving the livelihoods of pastoral community in particular.

4.4. Effects of elevations on carbon stocks accumulation

Several earlier studies (Richards; 1996; Luo et al., 2005; Alves et al., 2010) described the effect of elevation on diversity, biomass and soil carbon stock in the forest ecosystems. In the present study, it was demonstrated that the biomass carbon stocks showed decreasing pattern with increasing elevation. Similar studies were reported in other part of Ethiopia and elsewhere in the tropics (Luo et al., 2005; Zhu et al., 2011; Wolde et al., 2014; Yelemfrhat et al., 2014). This is likely associated to vegetation distribution, tree density, basal area, wood density and bigger diameter frequent that are linked with elevation ranges (Pan et al., 2013). Besides, decreasing availability of nutrients, especially nitrogen, has been suggested to limit tree height and biomass stocks with increasing elevation (Tanner et al., 1998). Furthermore, lack of inconsistent trend in litter carbon stocks along the elevation ranges may be due to the rate of decomposition, stand age and disturbance play more important role in regulation of litter pool size (Harmon et al., 1986). Thus, the biomass and carbon density of litter relatively peaked in middle elevation of the studied woodland ecosystem. Similar result was reported in Mt Changbai of China (Zhu et al., 2011). Similarly, the mean soil carbon stocks showed inconsistency trend along the elevation ranges. The higher proportion of SOC stocks at the middle elevations may be due to dominance of some species such as *Combretum molle* (D. Don), *Pistacia lentiscus* (Mart.), *Terminalia brownii* (Fresen.) and dense canopy, providing higher inputs of litter to the soils and hence, could enhance SOC stocks (Giliba et al., 2011; Grand and Lavkulich, 2011; Yao et al., 2010). Slightly lower mean soil organic carbon stock in lower elevation might be associated with species composition, the rate of litter decompositions and thus affect SOC stocks (Rojas et al., 2012).

5. Conclusions

The studied Combretum–Terminalia woodland ecosystem sinks high carbon stocks both in the biomass and soil than some other dryland vegetation reported in Ethiopia and elsewhere in the tropics. Soil accumulated above 67% of the total woodland ecosystem carbon stocks across the three elevations. Among the tree species recorded, *Acacia bussei* (Harms ex Sjöstedt), *Combretum molle* (D. Don), *Terminalia brownii* (Fresen.), *Pistacia lentiscus* (Mart.), *Acacia mellifera* (Vahl.) Benth. and *Commiphora erythraea* (Ehrenb.) Engl. contributed the larger share of the total biomass carbon stocks along the elevation ranges. More biomass carbon was accumulated in the lower elevation while the SOC stocks were high in middle and higher elevations. The present study revealed that the variation in elevation has significant effects on ecosystem carbon stocks, and more carbon accumulated in the soil than biomass and hence, the Combretum–Terminalia vegetation in the study region would play important role to preserve carbon in long-term while supporting the livelihoods of pastoral community. However, the ongoing heavy deforestation in this vegetation type for various purposes should be given attention to sustain the vegetation type and the various ecosystem benefits at large. Furthermore, this woodland ecosystem has a potential for emission reduction and hence, would serve to benefit from carbon financing schemes, and that would assist government's development strategies to sustainably management the dryland ecosystems.

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References

- Aide, T.M., Clark, M.L., Grau, H.R., López-Carr, D., Levy, M.A., Redo, D., Bonilla-Moheno, M., Riner, G., Andrade-Núñez, M.J., Muñiz, M., 2012. Deforestation and reforestation of Latin America and the Caribbean. *Biotropica* 45 (2), 262–271.
- Alemu, B., 2012. Carbon Stock Potentials of Woodlands and Land Use and Land Cover Changes in North Western Lowlands of Ethiopia Master's Thesis. University of Hawassa, Wondo Genet College of Forestry 39 & 79p.
- Allen, S.E., Grimshaw, H.M., Rowland, A.P., 1986. Chemical analysis. In: Moore, P.D., Chapman, S.B. (Eds.), *Methods in Plant Ecology*. Blackwell Scientific Publications, London, UK, pp. 285–344.
- Alves, L.F., Vieira, S.A., Scaranello, M.A., Camargo, P.B., Santos, F.A.M., Joly, C.A., Martinelli, L.A., 2010. Forest structure and live aboveground biomass variation along an elevation gradient of tropical Atlantic moist forest of Brazil. *For. Ecol. Manag.* 260, 679–699.
- Belay, L., Kebede, F., 2010. The impact of woody plants encroachment on soil organic carbon and total nitrogen stocks in Yabello District, Borana Zone, Southern Ethiopia. *J. Dry lands* 3 (2), 234–240.
- Brown, S., Lugo, A., 1982. The storage and production of organic matter in tropical forests and their role in the global carbon cycle. *Biotropica* 14 (3), 161–187.
- Cairns, M.A., Brown, S., Helmer, E.H., Baumgardner, G.A., 1997. Root biomass allocation in the world's upland forests. *Oecologia* 111, 1–11.
- Campbell, J.E., Lobell, D.B., Genova, R.C., Field, C.B., 2008. A global potential of bio-energy on abandoned agricultural land. *Environ. Sci. Technol.* 42 (15), 5791–5794.
- Chaiyo, U., Garivait, S., Wanthongchai, K., 2011. Carbon Storage in Above-ground Biomass of Tropical Deciduous Forest in Ratchaburi Province, Thailand, vol. 58. World Academy of Science, Engineering and Technology, pp. 636–641.
- Chave, J., Condit, R., Aguilar, S., Hernandez, A., Lao, S., Perez, R., 2004. Error Propagation and Scaling for Tropical Forest Biomass Estimates. vol. 359. *Philosophical Transactions of the Royal Society of London Series*, pp. 409–420.
- Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.P., Nelson, B.W., Ogawa, H., Puig, H., Riéra, B., Yamakura, T., 2005. Tree allometric and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* 145, 87–99.
- Chave, J., Rejou-Mechain, M., Burquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B.C., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C., Henry, M., Martinez-Yrizar, A., Mugasha, W.A., Muller-Landau, H.C., Mencuccini, M., Nelson, B.W., Ngomanda, A., Nogueira, E.M., Ortiz-malavassi, E., Pélissier, R., Ploton, P., Ryan, C.M., Saldarriaga, J.G., Vieilleden, G., 2014. Improved allometric Models to estimate the aboveground biomass of tropical trees. *J. Global Change Biol.* 20, 3177–3190.
- Ciais, P., Bombelli, A., Williams, M., Piao, S.L., Chave, J., 2011. The carbon balance of Africa: synthesis of recent research studies. *Phil. Trans. R. Soc.* 369, 1–20.
- Coppock, D.L., 1994. The Borana Plateau of Southern Ethiopia: Synthesis of Pastoral Research, Development and Change, 1980–1991. International Livestock Center for Africa, Addis Ababa, Ethiopia.
- Coûteaux, M.M., Mousseau, M., Célerier, M.L., Botner, P., 1991. Increased atmospheric CO and litter quality: decomposition of sweet chestnut leaf litter with animal food web of different complexity. *Oikos* 61, 54–64.
- Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C., Wisniewski, J., 1994. Carbon pools and flux of global forest ecosystems. *Science* 263, 185–190.
- Edwards, S., Sebsebe, D., Hedberg, I., 1997. Flora of Ethiopia and Eritrea, vol. 6 The National Herbarium, Addis Ababa University, Addis Ababa, Ethiopia and Department of Systematic Botany, Uppsala University, Uppsala, Sweden.
- Edwards, S., Mesfin, T., Sebsebe, D., Hedberg, I., 2000. Flora of Ethiopia and Eritrea, vol. 2 The National Herbarium, Addis Ababa University, Addis Ababa, Ethiopia and Department of Systematic Botany, Uppsala University, Uppsala, Sweden.
- Feyissa, A., Soromessa, T., Argaw, M., 2013. Forest carbon stocks and variations along altitudinal gradient in Egdu forest: implications of managing forests for climate change mitigation. *Sci. Technol. Arts Res. J.* 2 (4), 40–46.
- Fisher, R.F., Binkley, D., 2000. *Ecology and Management of Forest Soils*. John Wiley & Sons, Inc, New York, USA.
- Franks, P., 2017. Reconciling Forest Conservation with Food Production in Sub-Saharan Africa: Case Studies from Ethiopia, Ghana and Tanzania. IIED Research Report. London.
- Gibbs, H.K., Brown, S., Niles, J.O., Foley, J.A., 2007. Monitoring and estimating tropical forest carbon stocks: making REDD a reality. *Environ. Res. Lett.* 13, 045023.
- Giliba, R.A., Boon, E.K., Kayombo, J.C., Chirenje, L.I., Musamba, E.B., 2011. The influence of socio-economic factors on deforestation: a case study of the Bereku forest reserve in Tanzania. *J. Biodivers* 2 (1), 31–39.
- Gillespie, T., Lipkin, B., Sullivan, L., Benowitz, D., Pau, S., Keppel, G., 2012. The rarest and least protected forests in biodiversity hotspots. *Biodivers. Conserv.* 21 (14), 3597–3611.
- Girma, A., Soromessa, S., Bekele, T., 2014. Forest carbon stocks in woody plants of Mount

- Zequalla Monastery and its variation along altitudinal gradient: implication of managing forests for climate change mitigation. *Sci. Technol. Arts Res. J.* 3 (2), 132–140.
- Girmay, G., Singh, B.R., Mitiku, H., Borresen, T., Lal, R., 2008. Carbon stocks in Ethiopian soils in relation to land use and soil management. *Land Degrad. Dev.* 19, 351–367.
- Grand, S., Lavkulich, L.M., 2011. Depth distribution and predictors of soil organic carbon in podzols of a forested watershed in South western Canada. *J. Soil Sci.* 176 (4), 164–174.
- Hallo, B., Taddese, Z., Hoag, D., 2014. Carbon stocks in semi-arid pastoral ecosystems of northern Kenya. *Pastoralist J.* 4, 5.
- Harmon, M.E., Franklin, J.F., Swanson, E., Sollins, P., Gregory, S.V., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack, K., Cummins, K.W., 1986. Ecology of coarse woody debris in temperate ecosystems. *Adv. Ecol. Res.* 15, 133–302.
- Haugen, T., 1992. Woody vegetation of Borana, South Ethiopia. A study on the main vegetation types of the Borana. *Eth. J. Sci.* 15 (2), 117–130.
- Hedberg, I., Edwards, S., 1995. Flora of Ethiopia and Eritrea, vol. 7 The National Herbarium, Addis Ababa University, Addis Ababa, Ethiopia and Department of Systematic Botany, Uppsala University, Uppsala, Sweden.
- Henry, M., 2010. Carbon Stocks and Dynamics in Sub Saharan Africa. Ph.D. Dissertation. Paris Institute of Technology for Life, Food and Environmental Sciences (AgroParisTech) and the University of Tuscia, France.
- Houghton, R.A., 2007. Balancing the global carbon budget. *Annu. Rev. Earth Planet Sci.* 35, 313–347.
- Intergovernmental Panel on Climate Change (IPCC), 2007. Climate Change 2007, the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
- Intergovernmental Panel on Climate Change (IPCC), 2014. Climate Change 2014, Fifth Assessment Report, Mitigation of Climate Change.
- Knorr, W., Prentice, I.C., House, J.I., Holland, E.A., 2005. Long term sensitivity of soil carbon turnover to global warming. *Nature* 433, 298–301.
- Lal, R., 2005. Forest soil sand carbon sequestration. *For. Ecol. Manag.* 220, 242–258.
- Lal, R., Negassa, W., Lorenz, K., 2015. Carbon sequestration in soil. *Current Opin. Environ. Sustainability.* 15, 79–86.
- Lemenih, M., Teketay, D., 2004. Natural gum and resin resources: opportunity to integrate production with conservation of biodiversity, control of desertification and adapt to climate change in the drylands of Ethiopia. In: Paper Presented to the First National Workshop on Conservation of Genetic Resources of Non Timber Forest Products (NTFPs) in Addis Ababa, Ethiopia, 5–6 April 2004.
- Luo, T.X., Brown, S., Pan, Y.D., Shi, P.L., Ouyang, H., Yu, Z.L., Zhu, H.Z., 2005. Root biomass along subtropical to alpine ranges: global implication from Tibetan transects studies. *For. Ecol. Manag.* 206, 349–363.
- MacDicken, K.G., 1997. A Guide to Monitoring Carbon Emissions from Deforestation and Degradation in Developing Countries: an Examination of Issues Facing the Incorporation of REDD into Market-based Climate Policies. Resource for Future, Washington, DC.
- Mekuria, A., Demel, T., Mats, O., 1999. Soil seed flora, germination and regeneration pattern of woody species in an Acacia woodland of the Rift valley in Ethiopia. *J. Arid Environ.* 43, 411–435.
- Munishi, P.K.T., 2010. Working Paper Series. Climate Vulnerability of Biophysical and Socio-economic Systems in Woodlands and Savannas in Eastern and Southern Africa. African Forest Forum, vol. 2. pp. 46 6.
- Murphy, P.G., Lugo, A.E., 1986. Ecology of tropical dry forest. *Annu. Rev. Ecol. Systemat.* 17, 67–88.
- Nair, P.K.R., Kumar, B.M., Nair, V.D., 2009. Agroforestry as a strategy for carbon sequestration. *J. Plant Nutr. Soil Sci.* 172, 10–23.
- Pan, Y., Birdsey, R., Phillips, O., Jackson, R., 2013. The structure, distribution and biomass of the world's forest. *Annual Rev. Ecol. Evol. Syst.* 44, 593–622.
- Pearson, T., Walker, S., Brown, S., 2005. Source Book for Land-use, Land-use Change and Forestry Projects. Winrock International and the Bio-carbon fund of the World Bank, pp. 57.
- Richards, P.W., 1996. Tree species effects on soil properties in experimental plantations in tropical moist forest. *Soil Sci. Soc. Am. J.* 71, 1389–1397.
- Rojas, M.M., Jordan, A., Zavala, L.M., Rosa, D.D.L., Abd-Elmabod, S.K., Romero, M.A., 2012. Organic carbon stocks in Mediterranean soil types under different land uses Southern Spain. *Solid Earth.* 3, 375–386.
- Rosell, R.A., Gasparoni, J.C., Galantini, J.A., 2000. Soil organic matter evaluation. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), *Assessment Methods for Soil Carbon*. CRC/Lewis Publishers, Boca Raton, pp. 311–322.
- Ryan, C.M., Williams, M., Grace, J., 2010. Above and belowground carbon stocks in a Miombo woodland landscape of Mozambique. *Biotropica* 1–10.
- Saiz, G., Bird, M.I., Domingues, T., Schrodt, F., Schwarz, M., Feldpausch, T.R., Veenendaal, E., 2012. Variation in soil carbon stocks and their determinants across a precipitation gradient in west Africa. *Glob. Change Biol.* 18, 1670–1683.
- Sarah, G., 2012. Relationship between Vegetation Type, Soil Type, Soil Moisture and Carbon Stocks in Semi-arid Ethiopian Savannas: Borena Zone, Ethiopia. Master's thesis. University of Hohenheim, Faculty of Agricultural Sciences, pp. 28.
- Sheikh, M.A., Kumar, M., Bussmann, R.W., 2009. Altitudinal variation in soil organic carbon stock in coniferous subtropical and broad leaf temperate forests in Garhwal Himalaya. *Carbon Bal. Manag.* 4, 6.
- Shelukindo, H.B., Semu, E., Msanya, B.M., Singh, B.R., Munishi, P.K.T., 2014. Soil organic carbon stocks in the dominant soils of the Miombo woodland ecosystem of Kitonga Forest Reserve, Iringa, and Tanzania. *Int. J. Agric. Pol. Res.* 2 (4), 167–177.
- Smith, T.M., Cramer, W.P., Dixon, R.K., Leemans, R., Neilson, R.P., Solomon, A.M., 1993. The global terrestrial carbon cycle. *Water, Air and Soil Pollut.* 70, 19–38.
- Snowdon, P., Raison, J., Keith, H., Ritson, P., Grierson, P., Adams, M., Montagu, K., Bi, H.-Q., Burrows, W., Eamus, D., 2002. Protocol for Sampling Tree and Stand Biomass: National Carbon Accounting System. Technical report no. 31. Australian Greenhouse Office, Canberra, pp. 66.
- Tanner, E.V.J., Vitousek, P.M., Cuevas, E., 1998. Experimental investigations of nutrient limitation of forest growth on wet tropical mountains. *Ecology* 79, 10–22.
- UNFCCC, 1997. Kyoto Protocol to the Convention on Climate Change. Climate Change Secretariat, Bonn, Germany.
- Walkley, A., Black, C., 1934. Examination of the degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.* 37, 29–38.
- WBISPP, 2005. Woody Biomass Inventory and Strategic Planning Project: a National Strategic Plan for the Biomass Sector. Ministry of Agriculture, Addis Ababa, Ethiopia.
- Weaver, P., Murphy, P., 1990. Forest structure and productivity in Puerto Rico's Luquillo Mountains. *Biotropica* 22, 69–82.
- Williams, M., Ryan, C., Rees, R., Sambane, E., Fernando, J., Grace, J., 2008. Carbon sequestration and biodiversity of re-growing miombo woodlands in Mozambique. *For. Ecol. Manag.* 254, 145–155.
- Wolde, B.M., Kelbessa, E., Soromessa, T., 2014. Forest carbon stocks in woody plants of Arba Minch ground water forest and its variations along environmental gradients. *Sci. Technol. Arts Res. J.* 3 (2), 141–147.
- World Meteorological Organization (WMO), 2014. The State of Green House Gas in the Atmosphere Based on Global Observation.
- Yao, M.K., Angui, P.K.T., Konate, S., Tondoh, J.E., Tano, Y., Abbadie, L., Benest, D., 2010. Effects of land use types on soil organic carbon and nitrogen dynamics in Mid-West Cote d'Ivoire. *Eur. J. Sci. Res.* 40 (2), 211–222.
- Yelemfrhat, T., Soromessa, T., Bayable, E., 2014. Forest carbon stocks in lowland area of simien mountains national park implication for climate change mitigation. *Sci. Technol. Arts Res. J.* 3 (3), 29–36.
- Yitebitu, M., Zewdu, E., Sisay, N., 2010. Ethiopian Forest Resource: Current Status and Future Management Options. Addis Abeba, Ethiopia).
- Zanne, A.E., Lopez-Gonzalez, G., Coomes, D.A., Ilic, J., Jansen, S., Lewis, S.L., Miller, R.B., Swenson, N.G., Wiemann, M.C., Chave, J., 2009. Towards a worldwide wood economics spectrum. *Ecol. Lett.* 12 (4), 351–366.
- Zhu, B., Xiangping, W., Jingyun, F., Shilong, P., Haihua, S., Shuqing, Z., Changhui, P., 2011. Altitudinal changes in carbon storage of temperate forests on Mt Changbai, Northeast, China. *J. Plant Resour.* 10, 1–14.